Cognition and Neuroscience

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Alma Mater Studiorum · University of Bologna

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Acronyms

AP action potential

EPSP excitatory postsynaptic potential

IPSP inhibitory postsynaptic potential

PSP postsynaptic potential

1 Introduction

1.1 Definitions

Neuroscience Study of the nervous system (structure aspects) on various levels of detail: Neuroscience

- **Molecular** Proteins and molecular signaling of the nervous system.
- **Cellular** Morphological and physiological properties of neurons.
- **Neural system** Creation and functioning of networks of neurons.

Cognition Mental processes (function aspects) that react to inputs. It involves processes regarding the acquisition, storage, manipulation, and retrieval of information. Cognition

- **Perception** Information from the environment.
- **Attention** Focus on a specific stimulus in the environment.
- **Learning** Merging new information with prior knowledge.
- **Memory** Encoding, storing, and retrieving information.
- **Action** Interact with the environment using perceived information.
- **Language** Understanding and producing spoken or written thoughts.
- **Higher reasoning** Decision-making and problem-solving.

Biomimicry Solving problems by taking inspiration from elements of nature. Biomimicry

As proof of general intelligence[1], the human brain is taken as the model for artificial intelligence. Moreover, a successful brain-inspired AI application can provide a possibly plausible explanation of the functioning of the brain.

However, a brain differs from a computer in many aspects:

- Hardware and software are distinct while mind and brain are not.
- Machines learn by exploiting the capability of using a large memory while brains have limited capacity but high generalization ability.
- Brains produce both electrical and biochemical signals and have feedforward, feedback, and recurrent connections while machines typically only employ feedforward connections.

Structure emulation Mimic or reverse engineer the structure of the brain (e.g. Blue Brain Project).

Function emulation Mimic a neural system on the algorithmic level (e.g. Deep Mind).

Cognitive neuroscience Study of the relationship between the physical brain and the intangible mind (thoughts, ideas). In other words, it studies the relationship between structure and function. Cognitive neuroscience

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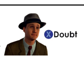
[1] 

Example (Severed Corpus Callosum[2]). Normally, the right and left hemispheres of the brain can communicate. Moreover, the left visual field is sent to the right hemisphere and the right visual field is sent to the left hemisphere.

In patients where the hemispheres are split, a text shown on the right visual side is recognized as the speech capabilities are located in the left hemisphere, while a text shown on the left visual side does not trigger any speech reaction.

1.2 Neuroscience history

Two main schools of thought emerged and are still the subject of ongoing debates:

Localizationism Specific regions of the brain are responsible for particular faculties. Localizationism

Assuming localizationism, 52 distinct regions with different neurons can be identified.

Aggregate field theory The brain works as a whole for mental functions. Aggregate field theory

1.2.1 Neuron doctrine

The nervous system is made of a discrete amount of individual neurons (and not a continuous tissue). Neuron doctrine

Principle of dynamic polarization Electrical signals in a neuron flow only in a single direction.

Principle of connectional specificity Neurons do not connect randomly but make specific connections at particular contact points.

Synapse Point of contact of two neurons. A synapse can be chemical or electrical. Synapse

1.3 Cognitive science history

Rationalism All knowledge can be derived through reasoning, without sensory experiences. Rationalism

Empiricism The brain starts as a blank slate and knowledge is added through sensory experiences. Empiricism

Associationism Inspired by empiricism. Learning happens by correlating individual experiences (e.g. actions followed by a reward will be repeated). Associationism

Behaviorism Inspired by empiricism. Everyone has the same neural basis that is improved through learning. Learning only involves observable behaviors. Behaviorism

Remark. Associationism and behaviorism are not able to explain all types of learning (e.g. language).

Cognitivism The psychological and biological levels of an individual cannot be separated. Learning is based on the biology of the neurons. Cognitivism

[2] `https://www.youtube.com/watch?v=lfGwsAdS9Dc`

2 Nervous system anatomy and physiology

Central nervous system Brain and spinal cord.

Peripheral nervous system Nerves that branch off from the brain and the spine.

2.1 Individual cells

2.1.1 Glia cells / Neuroglia

Glia cells/Neuroglia

Cells that support neurons. There are 2 to 10 times more glia cells than neurons.

Microglia

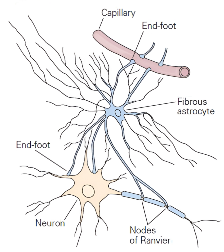
Microglia Immune system cells located in the central nervous system. They intervene in response to toxic agents or to clear dead cells.

- Responsible for antigen presentation (determine the type of external agent).
- Become phagocytes (cells that ingest harmful agents) during injuries, infections, or degenerative diseases.

Remark. In patients affected by Alzheimer's disease, microglia may become hyperactive and damage neurons.

Astrocytes

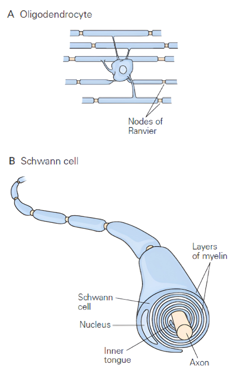
Astrocytes Star-shaped cells located in the central nervous system. They surround neurons and are in contact with the brain's vasculature.



- Provide nourishment to neurons.
- Regulate the concentration of ions and neurotransmitters in the extracellular space.
- Communicate with the neurons to modulate synaptic signaling.
- Maintain the blood-brain barrier that separates the tissues of the central nervous system and the blood.

Oligodendrocytes
Schwann cells

Oligodendrocytes and Schwann cells Oligodendrocytes are located in the central nervous system, while Schwann cells are located in the peripheral nervous system.



- Produce thin sheets of myelin that wrap concentrically around the axon of the neurons. This insulating material allows the rapid conduction of electrical signals along the axon.

Remark. Myelin is white, giving the name to the white matter.

Remark. In multiple sclerosis, the immune system attacks the oligodendrocytes, slowing or disrupting messages traveling along the nerves.

2.1.2 Neurons / Nerve cells

A nervous system has around 100 billion neurons. There are 100 distinct types of neurons varying in form, location, and interconnectivity. Neurons/Nerve cells

Generally, a neuron does the following:

1. Receives some information.
2. Makes a decision.
3. Passes it to other neurons.

Eukaryotic cell A neuron is an eukaryotic cell. Therefore, it has: Eukaryotic cell

- **Cell membrane** Membrane that separates the intracellular and extracellular space.
- **Cytoplasm** Intracellular fluid mainly made of proteins and ions of potassium, sodium, chloride, and calcium.
- **Extracellular fluid** Fluid in which the neuron sits. Similar composition of the cytoplasm.
- **Cell body/soma** Metabolic center of the cell.

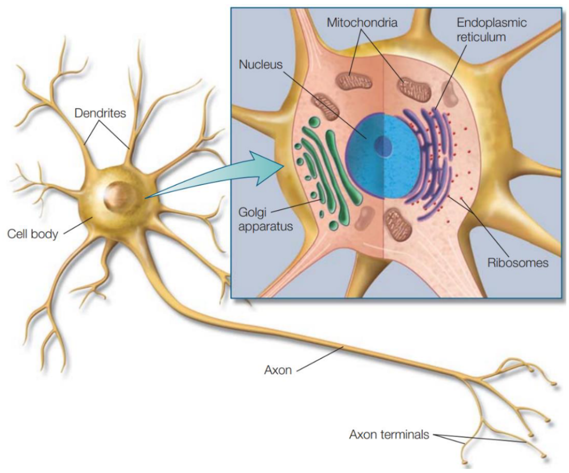


Figure 2.1: Neuron as an eukaryotic cell

Neuron-specific components

- **Dendrites** Receives the outputs of other neurons. A neuron has multiple dendrites with different shapes depending on the type and location of the neuron. Dendrites
- **Axon** Transmitting zone of the neuron that carries electrical signals from the dendrites to the synapses (from 0.1mm to 2m). A neuron has a single axon. Axon
- **Synapses** Represents the output zone of the neuron from where electrical or chemical signals can be transmitted to other cells. A neuron has multiple synapses. Synapses
  - **Presynaptic cell** Cell transmitting a signal.
  - **Postsynaptic cell** Cell receiving a signal.
  - **Synaptic cleft** Narrow space separating presynaptic and postsynaptic cells (i.e. the space separating two neurons).

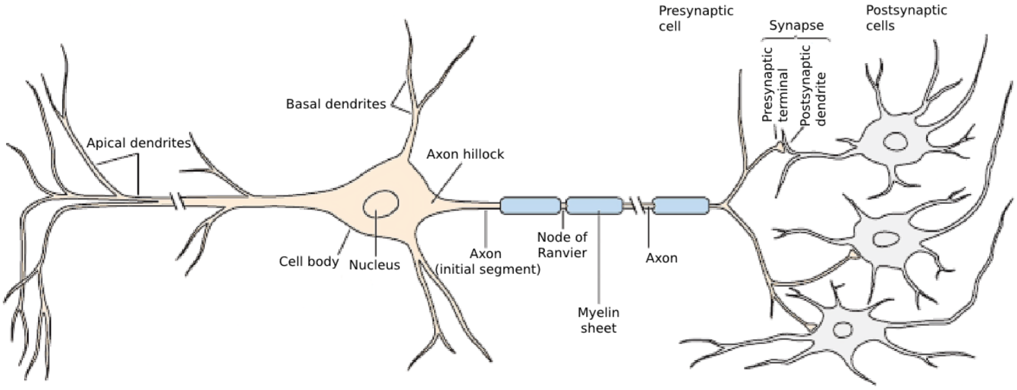


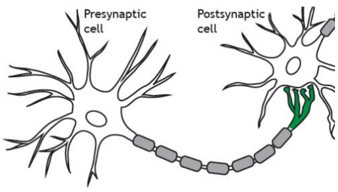
Figure 2.2: Neuron-specific components

There are three types of synapses:

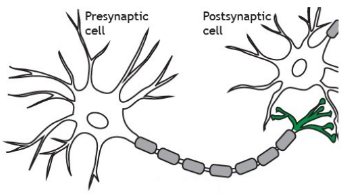
Axosomatic Synapses that a neuron makes onto the cell body (soma) of another neuron. Axosomatic

Axodendritic Synapses that a neuron makes onto the dendrites of another neuron. Axodendritic

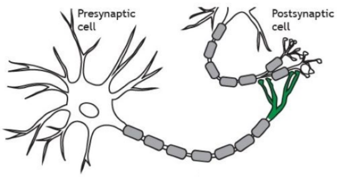
Axoaxonic Synapses that a neuron makes onto the synapses of another neuron. In this case, the transmitting neuron can be seen as a signal modulator of the receiving neuron. Axoaxonic



(a) Axosomatic



(b) Axodendritic



(c) Axoaxonic

Neurons are divided into three functional categories:

Sensory neurons Carry information from the body's peripheral sensors into the nervous system. Provides both perception and motor coordination. Sensory neurons

Motor neurons Carry commands from the brain or the spinal cord to muscles and glands. Motor neurons

Interneurons Intermediate neurons between sensory and motor neurons. Interneurons

Principle of connectional specificity Neurons do not connect randomly but rather make specific connections at particular contact points. Principle of connectional specificity

2.2 Information transfer within a neuron

2.2.1 Neuron functional regions

In a neuron, there are four regions that handle signals:

Input zone Dendrites collect information from different sources in the form of postsynaptic potentials (PSPs). Input zone

Integration/trigger zone PSPs are summed at the axon hillock and an action potential (AP) is generated if a threshold (-55mV) has been exceeded.

Integration/trigger zone

Conductive zone The AP is propagated through the axon.

Conductive zone

Output zone Synapses transfer information to other cells.

Output zone

Chemical synapses The frequency of APs determines the amount of neurotransmitters released.

Electrical synapses The AP is directly transmitted to the next neurons.

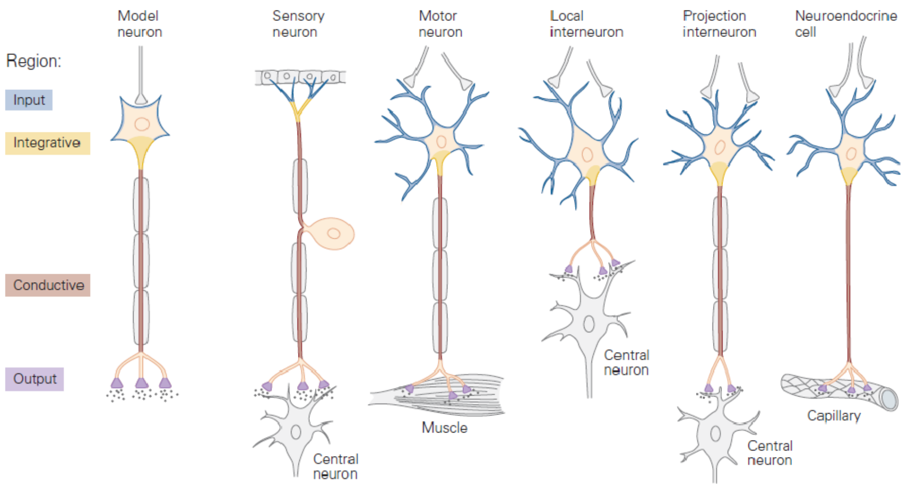


Figure 2.4: Transmitting regions of different types of neurons

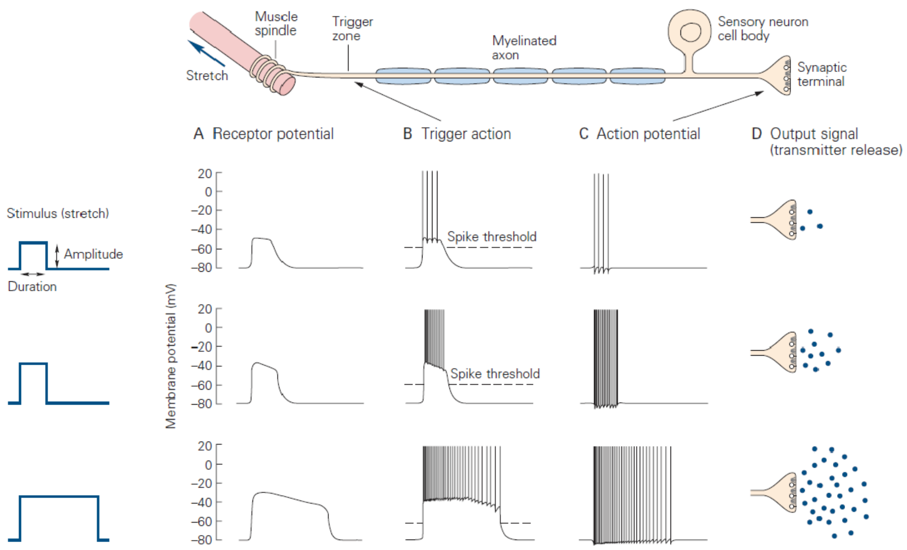


Figure 2.5: Signal from the input to the output zones

2.2.2 Neuron transmission signals

Resting membrane potential In a resting neuron, the voltage inside the cell is more negative (-70mV) than the outside. This allows the creation of an electrical signal when needed.

Resting membrane potential

Postsynaptic potential (PSP) Small change in the membrane potential that alters the resting voltage of the cell.

Postsynaptic potential (PSP)

A PSP can be:

Excitatory PSP (EPSP) Has a depolarizing role: produces a decrease in the membrane potential (i.e. increases voltage inside the cell), therefore enhancing the ability to generate an AP.

Excitatory PSP

Inhibitory PSP (IPSP) Has a hyperpolarizing role: produces an increase in the membrane potential (i.e. reduces voltage inside the cell), therefore reducing the ability to generate an AP.

Inhibitory PSP

A PSP has the following properties:

- The amplitude and duration of the signal are determined by the size of the stimulus that caused it. Overall, the amplitude is small.
- The signal is passively conducted through the cytoplasm, therefore it decays with distance and is able to travel 1mm at most.
- A single EPSP is not enough to fire a neuron. Multiple PSPs are summed at the axon hillock. There are two types of summation:

  Spatial summation Sum of the PSPs received at the same time.

  Temporal summation Sum of the PSPs received at different time points.

  Remark. The fact that a single EPSP is not enough to fire a neuron prevents a response to every single stimulus.

Action potential (AP) Signal generated when the sum of EPSPs exceeds a fixed threshold of -55mV (all-or-none).

Action potential (AP)

Saltatory conduction Mechanism that allows a fast propagation on long distances of APs.

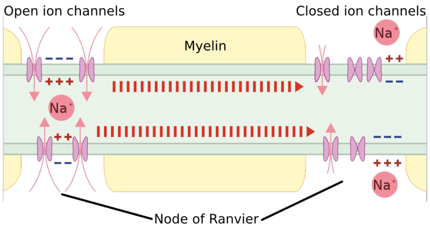
Saltatory conduction

1. Depolarization causes the sodium ion (Na+) channels located in the nodes of Ranvier of the axon to gradually open.
2. Na+ flows into the neuron and further depolarizes it until the Na+ equilibrium potential is reached.
3. With Na+ equilibrium, Na+ channels close and potassium ion (K+) channels open.
4. K+ flows into the neuron and restores the membrane potential until the K+ equilibrium potential is reached.
5. With K+ equilibrium, K+ channels close and the membrane potential of the neuron is more negative than the resting potential (hyperpolarization). It will gradually return to its resting potential.

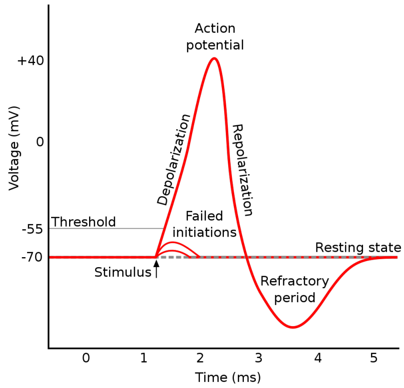
   Remark. During hyperpolarization, Na+ channels cannot open (refractory period). This has two implications:

   - It limits the number of times a neuron can fire in a given time.
   - Guarantees a unidirectional electrical current flow (**Principle of dynamic polarization**).

Principle of dynamic polarization



(a) Ion channels along the axon



(b) Triggering of an action potential

Remark. As the signal is constantly regenerated, APs have similar amplitude and duration in all neurons, regardless of the characteristics of the input PSPs. Therefore, the only way an AP has to carry information is by varying frequency and firing duration, making it a binary signal.

Example. Seizures are caused by misfiring neurons.